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EXPERIMENTAL PERFORMANCE EVALUATION OF A 6.02-INCH (15.29-CM) RADIAL-INFLOW TURBINE WITH AN EXIT DIFFUSER

by Samuel M. Futral, Jr., and Donald E. Holeski

Lewis Research Center
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SUMMARY

A performance evaluation of a 6.02-inch (15.29-cm) tip diameter radial-inflow turbine with an exit diffuser was made. The evaluation used argon as the working fluid and covered a range of speeds and pressure ratios. Turbine inlet conditions were fixed at values corresponding to design Reynolds number for design equivalent speed and design pressure ratio operation.

Results of the investigation indicated that, at design equivalent speed and pressure ratio, the turbine static efficiencies before and after diffusion were 0.825 and 0.865, respectively. The results also indicated a decrease in total efficiency of approximately 2 percent across the diffuser with the leaving loss accounting for less than 1 percentage point in the efficiency.

The ratio of diffuser static pressure recovery to the diffuser inlet impact pressure was approximately 0.6. This recovery is about 71 percent of the isentropic incompressible value for the same area ratio.

INTRODUCTION

The Lewis Research Center is presently conducting studies on a power generation system based on the closed Brayton cycle of a size suitable for use with a solar energy heat source. A description of a two-shaft system for a 10-kilowatt shaft power output is described in reference 1.

Various components are being investigated experimentally, both as isolated components and in combinations. One component is a 6.02-inch (15.29-cm) radial-inflow turbine designed to drive the compressor of this two-shaft system. References 2 and 3 present a description of this turbine and its associated performance over a wide range of Reynolds number.

In the two-shaft system, a transition section is required for ducting the working fluid from the compressor-drive turbine to the alternator-drive turbine. Since the entrance area of the alternator-drive turbine is larger than the exit area of the compressor-drive turbine for this particular design, the transition piece becomes a diffuser. Since the earlier tests were performed with a straight exit section installed on the compressor-drive turbine, the present investigation included the turbine performance with an exit diffuser.

The performance evaluation of the 6.02-inch (15.29-cm) radial-inflow turbine with the exit diffuser installed is reported here. Tests were conducted at a fixed turbine inlet total pressure and total temperature corresponding to design turbine Reynolds number at design equivalent speed and pressure ratio.

SYMBOLS

g gravitational constant, 32.174 ft/sec^2

$\Delta h'$ specific work, Btu/lb; J/kg

J mechanical equivalent of heat, 778.029 ft-lb/Btu

N rotative turbine speed, rpm

p pressure, psia; N/cm^2

Re Reynolds number, $w/\mu r_t$

r radius, ft; cm

T absolute temperature, $^{\circ}R$; $^{\circ}K$

U blade velocity, ft/sec; m/sec

w mass flow, lb/sec; kg/sec

α absolute gas flow angle, measured from meridional direction, positive when tangential velocity component agrees with direction of rotation, deg

ν blade-jet speed ratio, based on rotor tip speed, $U_t/\sqrt{2gJ\,\Delta h_{id,s,1-2}}$

η turbine efficiency

η_s static efficiency (based on total- to static-pressure ratio)

η_T total efficiency (based on total- to total-pressure ratio)

μ gas viscosity, lb/(ft)(sec); (N)(sec)/m^2

Subscripts:

id ideal

s static

t tip

1 station at turbine inlet (see fig. 4)

2 station at rotor exit (see fig. 4)

3 station at diffuser exit (see fig. 4)

Superscript:

' absolute total state

TURBINE DESCRIPTION

Turbine

A detailed description of this turbine is given in reference 2. The design values are given in table I.

TABLE I. - TURBINE DESIGN VALUES

Design parameters[a]	U.S. customary units	SI units
Total efficiency, η_T	0.880	0.880
Static efficiency, η_S	0.824	0.824
Total- to total-pressure ratio, p_1'/p_2'	1.560	1.560
Total-to static-pressure ratio, p_1'/p_2	1.613	1.613
Turbine speed, N	38 500 rpm	38 500 rpm
Specific work, Δh	34.73 Btu/lb	80.84×10^3 J/kg
Argon mass flow, w	0.611 lb/sec	0.277 kg/sec
Inlet total temperature, T_1'	1950° R	1083° K
Inlet total pressure, p_1'	13.20 psia	9.101 N/cm^2 abs
Blade-jet speed ratio, ν	0.697	0.697
Reynolds number, Re	63 700	63 700

[a]Based on rotor exit conditions.

Diffuser

The geometry of the diffuser was governed largely by the geometry of the two turbines in the system. Since the diffuser was to be essentially a transition piece connecting the two turbines, its entrance and exit areas as well as its diameters were fixed by the turbines. The diffuser entrance geometry conformed to that of the compressor-drive turbine, while its exit geometry conformed to that of the alternator-drive turbine. Packaging requirements for the system limited the length of the diffuser to 9 inches (22.86 cm).

The area variation shown in figure 1 was adopted to provide a continuous velocity

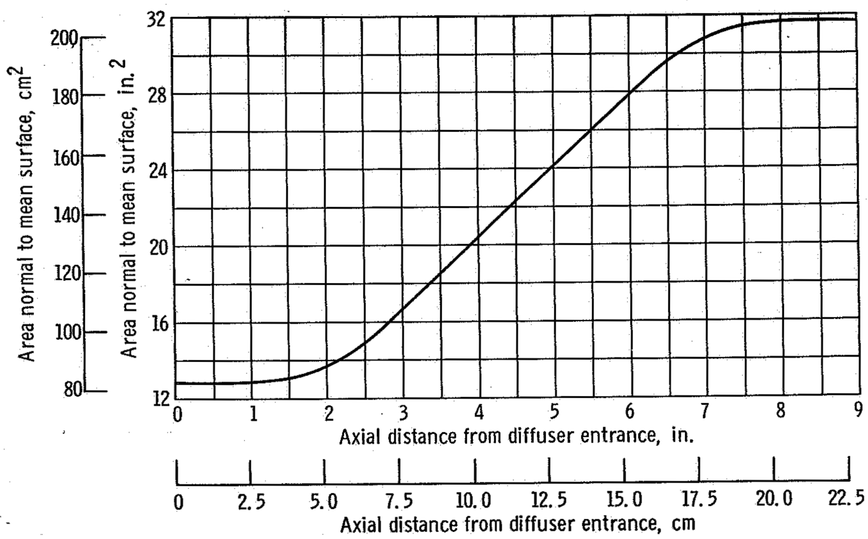

Figure 1. - Diffuser flow area distribution.

change through the diffuser. There is a 1-inch (2.54-cm) straight section at the diffuser entrance and another at the exit. In the middle section of the diffuser, the area varies linearly with axial distance. Circular arcs connect the linear sections. A generally similar curve was specified for the mean surface of the passage. A cross section of the diffuser passage in a plane through the axis is shown in figure 2. The inner and outer walls of the passage were determined by imposing the area variation of figure 1 on the indicated mean surface.

A photograph of the disassembled diffuser is shown in figure 3, and a sectional view of the turbine and diffuser is shown in figure 4. The struts which support the inner body are located entirely downstream of the diffuser.

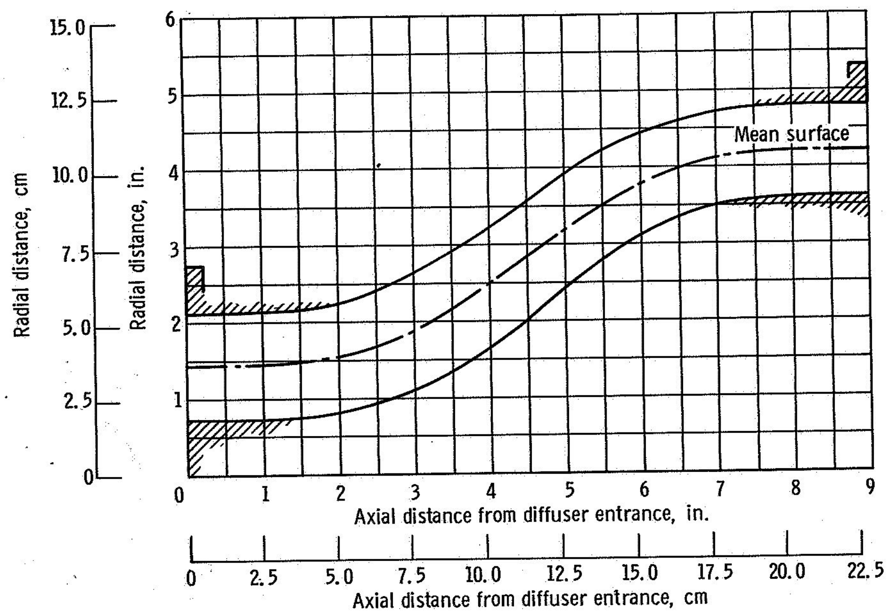

Figure 2. - Diffuser geometry.

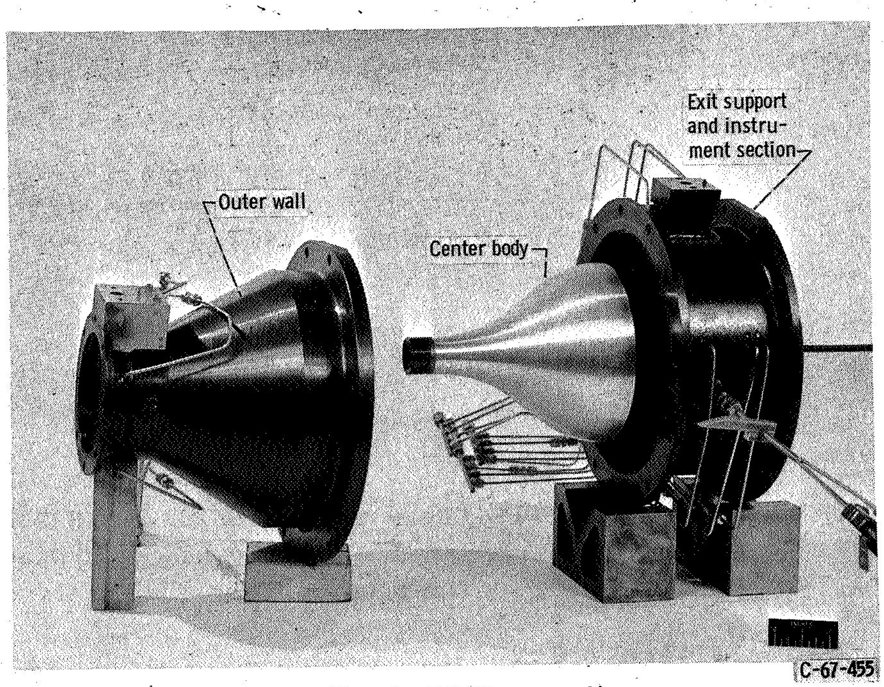

Figure 3. - Exit diffuser assembly.

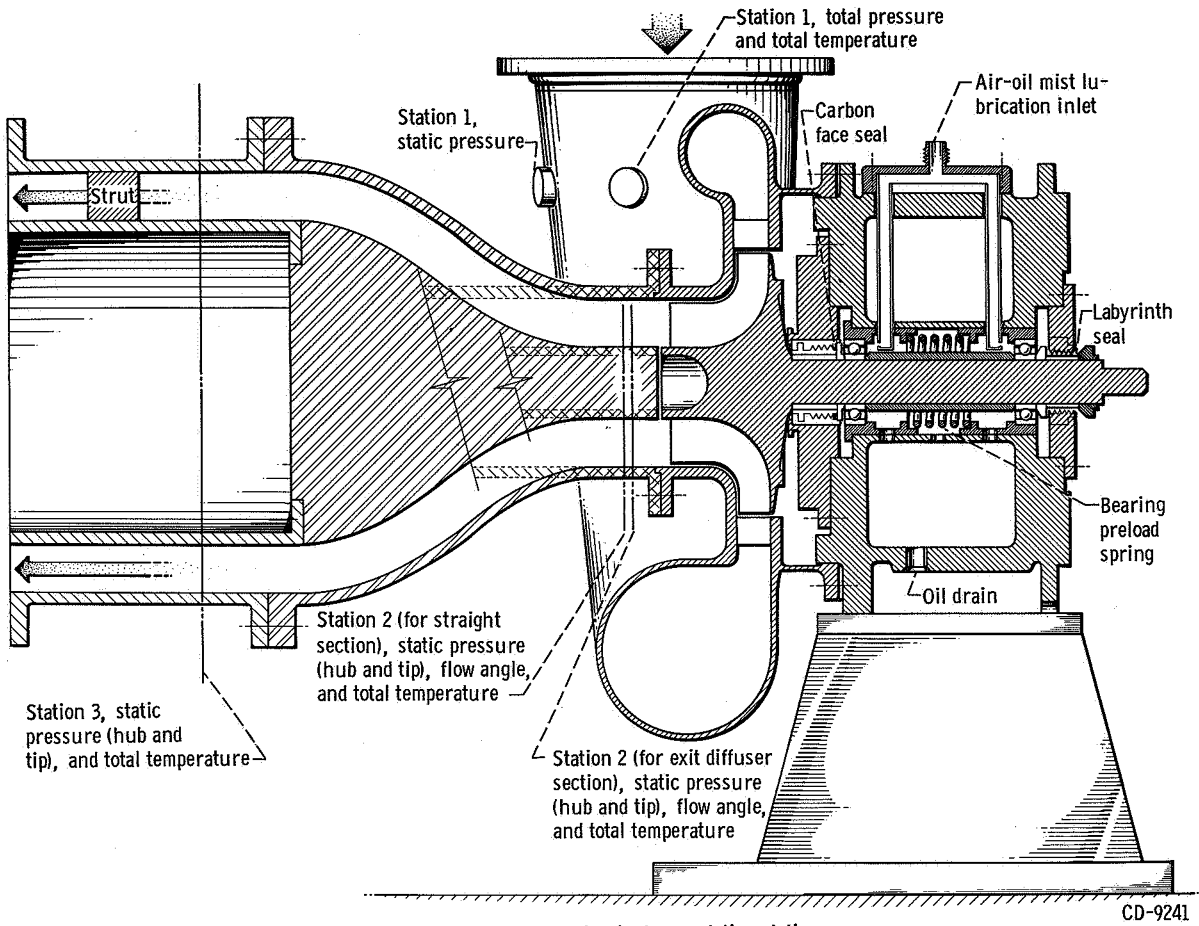

Figure 4. - Turbine showing instrumentation stations.

APPARATUS, INSTRUMENTATION, AND PROCEDURE

Apparatus

The apparatus consisted of the radial-inflow turbine and air-brake dynamometer, described in references 2 and 3, to which was added the diffuser described in the previous section. Figure 5 shows the turbine test facility with the diffuser in place.

Instrumentation

The instrumentation was also the same as that described in references 2 and 3, except that provisions were made for instrumenting the diffuser. The measuring station locations are shown in figure 4. Also shown in phantom in the figure is the straight exit

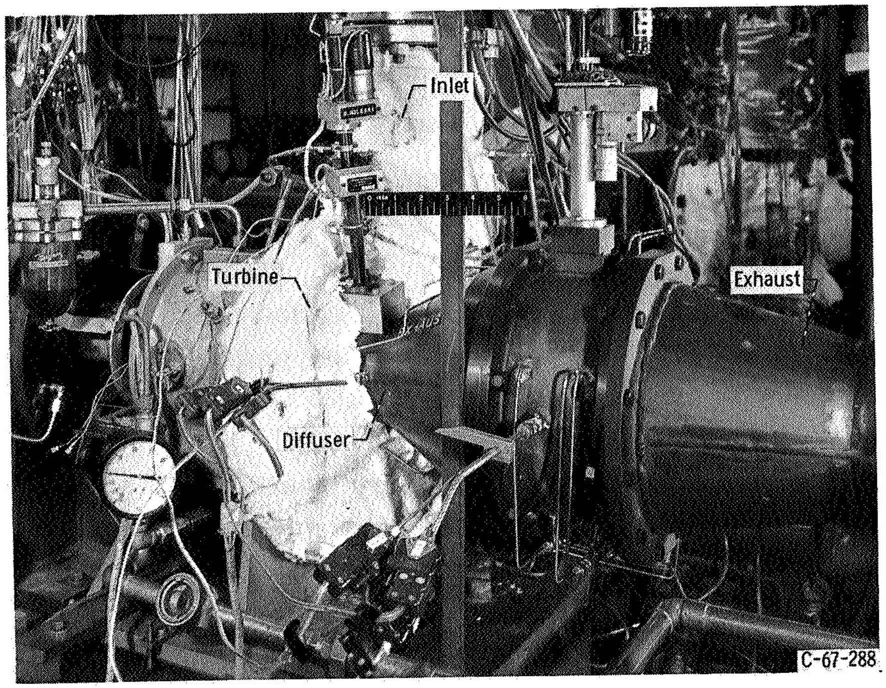

Figure 5. - Turbine test facility.

section that was used in references 2 and 3. Station 2 position for this study is slightly different from that used with the straight exit section. With the exit diffuser attached, station 2 was located nearer the rotor in order that its location would be in a straight section so that the effects of wall curvature on pressure readings would be minimized. Station 3 was also located in a straight section at the diffuser exit. For the turbine performance tests, static taps at the turbine inlet, diffuser inlet, and diffuser exit were used.

For the design speed survey tests, in addition to the abovementioned instrumentation, a mounting pad for radial survey instrumentation was added at the diffuser inlet. This instrumentation consisted of a self-balancing probe so that the flow angle, total pressure, and total temperature could be measured. Similar instrumentation was installed at the diffuser exit.

All turbine pressures were measured by manometers. These manometers contained a fluid with a specific gravity near 1 and a low vapor pressure at room temperature. The manometers were calibrated to an accuracy of 0.002 psia (0.001 N/cm^2 abs). Pressure measurements were taken with the reference side of each manometer evacuated to a pressure of 10 microns of mercury (1.333×10^{-4} N/cm^2).

The mass flow was measured by means of a calibrated choked flow nozzle, with the nozzle pressure measured by a calibrated pressure transducer. A rake of three thermocouples situated at the scroll entrance was used to measure the turbine total temperature. All other data were measured in the same manner as reported in references 2 and 3, recorded by an automatic digital potentiometer. The data processing was done through a digital computer.

Procedure

In order to obtain conventional performance data, constant speed runs were made at speeds of 40, 60, 70, 80, 90, 100, and 110 percent of design speed using argon as the working fluid. For all speeds, the inlet total pressure was held at 3.4 psia (2.34 N/cm^2), and the inlet total temperature was held at 630° R (350° K). These inlet conditions correspond to a design Reynolds number of 63 700. The exit pressure was varied to obtain ratios of inlet total pressure to exit static pressure from 1.4 to 2.1. Inlet total pressure was calculated from the measured static pressure, temperature, and mass flow rate. Data resulting from the measurements were used to calculate the static efficiency of the turbine, before and after diffusion.

In order to make a more detailed investigation of the performance of the turbine and diffuser, surveys were conducted at both the rotor and diffuser exit. A complete survey was made for each of three different total- to static-pressure ratios at design equivalent speed. The surveys consisted of measurements of total pressure, flow angle, and total temperature taken at 16 different radii. The radii used were the rms radii for 16 equal annular areas. For each pressure ratio, steady-state conditions were maintained as closely as possible throughout the turbine and diffuser, while the data were taken at the 16 radii in sequence. All other data, such as torque, speed, and static pressures were taken at the same time as the survey data for each radius.

Turbine efficiencies were computed for each pressure ratio from the arithmetic averages of the 16 values of static pressure, torque, speed, and turbine inlet temperature taken during the surveys. For total pressure and flow angle at the diffuser inlet, mass-weighted mean values were calculated. In order to do this, the mass flow rate was calculated from the measured local total pressure, temperature, and angle for each of the 16 annular areas. The mass flow rates were then used as weighting factors in the calculation of mean values for total pressure and angle. Thus, all data used in calculations involving the station at the diffuser inlet were either the arithmetic average for 16 readings or the mass-average values.

The radial traverse measurements at the diffuser exit were made in the same manner as described for the station at the diffuser inlet. The distribution of total pressure across the flow channel was measured and the data were considered reliable on the basis of reproducibility. However, good measurements of flow angle could not be obtained because of the inability of the instrumentation to respond correctly to the low velocities that were present at the diffuser exit. A typical example of these low velocities is the case where

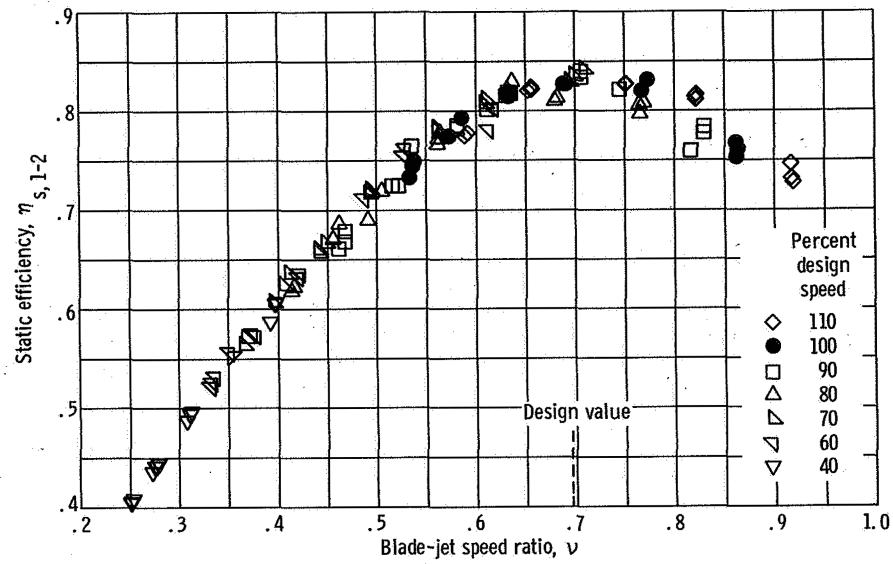

Figure 6. - Static efficiency characteristics of turbine before diffusion.

the difference between total and static pressures was approximately 0.01 psi (0.007 N/cm^2). Since calculations based on ideal flow indicated that there should be no significant change in flow angle through the diffuser, the mass-average angle obtained at the diffuser entrance was used to calculate an average value of total pressure at the diffuser exit. This value was used in the calculation of overall total efficiency across the turbine.

Blade-jet speed ratio, used in the presentation of results, was calculated in all cases from the ratio of turbine inlet total pressure to rotor exit static pressure. Thus, comparisons of results were facilitated where efficiencies are presented based on conditions at the rotor exit as well as at the diffuser exit.

RESULTS AND DISCUSSION

The results and discussion section is presented in three parts. The first part describes the static and total efficiency characteristics of the turbine based on conditions at both the rotor and diffuser exit. The results include those obtained from overall measurements as well as from the radial survey. The second part describes the radial variation in flow conditions at the rotor and diffuser exit, as obtained from the radial surveys. The third part then describes the effectiveness of the diffuser in converting the inlet impact pressure to static pressure.

Overall Performance Results

The performance of the turbine with the exit diffuser is presented in figures 6 and 7.

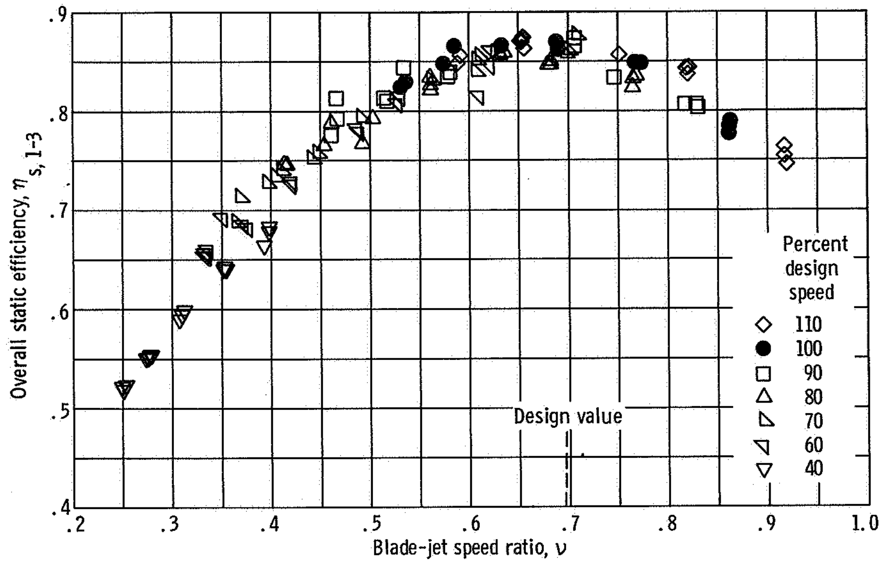

Figure 7. - Overall static efficiency characteristics of turbine.

The variation of turbine static efficiency before diffusion, $\eta_{s,1-2}$, with blade-jet speed ratio ν is shown in figure 6. At design equivalent speed and design blade-jet speed ratio the turbine static efficiency was 0.825. This efficiency is in close agreement with the value of 0.83 obtained in reference 2. The variation of overall static efficiency, $\eta_{s,1-3}$, with blade-jet speed ratio is shown in figure 7. At design equivalent speed and design blade-jet speed ratio the overall static efficiency was 0.865 indicating approximately a 4-point increase in static efficiency across the diffuser. The overall static efficiency is up to 11 points higher than that before diffusion over the range of blade-jet speed ratios investigated as a result of the pressure recovery that occurs through the diffuser.

Figure 8 presents total and static efficiencies plotted against blade-jet speed ratio as obtained from the 16-point radial surveys taken at three pressure ratios and at design equivalent speed. At design blade-jet speed ratio, the turbine static and total efficiencies before diffusion are seen to be 0.822 and 0.887, respectively. This difference in static and total efficiency is about $6\frac{1}{2}$ percentage points and represents the kinetic energy level at the rotor exit. The 0.887 total efficiency before diffusion compares closely with the 0.88 value described in reference 2.

The overall static efficiency $\eta_{s,1-3}$ at design blade-jet speed ratio is also seen to be 0.857, while the overall total efficiency $\eta_{T,1-3}$ is 0.865. The difference in static and total efficiency is therefore less than 1 percentage point at the diffuser exit. This difference represents the kinetic energy level at the diffuser exit and is considerably lower than that obtained at the rotor exit. The total efficiency across the turbine and diffuser is always lower than that across the turbine as a result of the total-pressure loss through the diffuser. Thus, at design blade-jet speed ratio, the overall turbine total efficiency is seen to be about 2 points lower than that before diffusion. The values of the static effi-

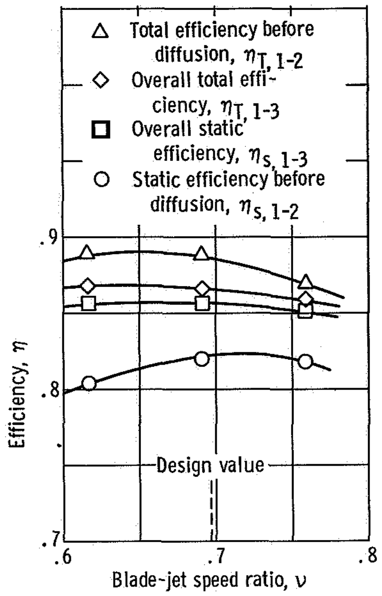

Figure 8. - Turbine efficiency characteristics as obtained from radial survey data.

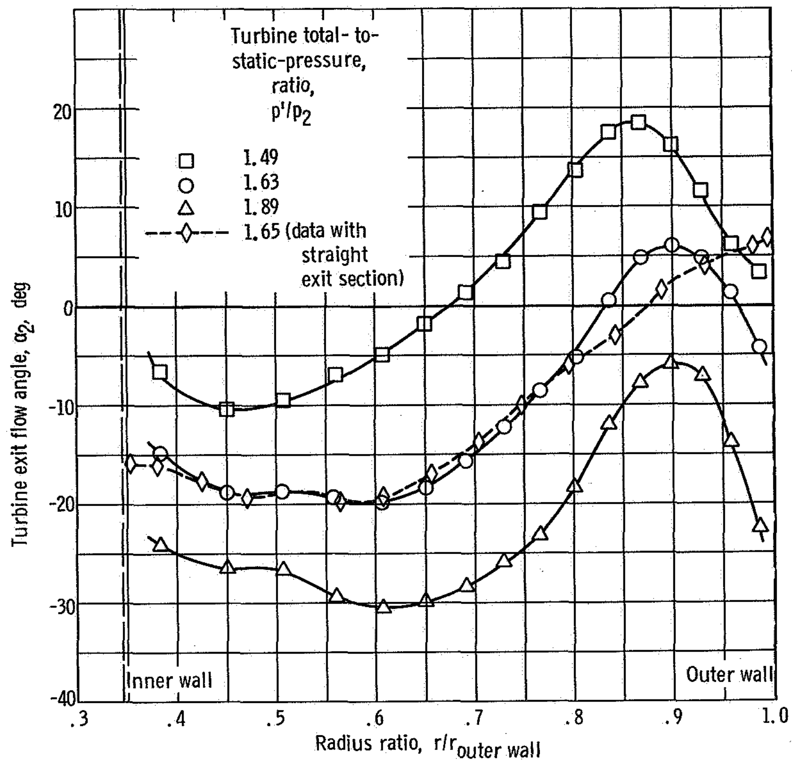

Figure 9. - Variation of turbine exit flow angle with radius ratio.

ciencies presented differ slightly from those presented in figures 6 and 7 as the result of experimental error, the maximum difference being about 0.8 of a percentage point.

Results of Radial Surveys

The radial surveys made behind the rotor (station 2) were also used to study the flow conditions at the rotor exit. In addition, total pressure surveys were made at the diffuser exit to determine the total pressure characteristics at this station (3).

Figure 9 presents the radial variation in flow angle at station 2 with the turbine operating at design equivalent speed and at total- to static-pressure ratios of 1.49, 1.63, and 1.89. The flow angle variation is seen to be similar for the three pressure ratios investigated. Previously unpublished data of the radial variation in flow angle with the straight exit section is also shown plotted as a dashed line. These data were taken at the same turbine inlet conditions and a pressure ratio of 1.65, and can be compared with that taken at a pressure ratio of 1.63. It may be seen that the curves are similar with only a small deviation occurring near the outer wall.

Figure 10 presents the variation in measured total pressure at the rotor exit with radial position for the three pressure ratios investigated. The measured values of total

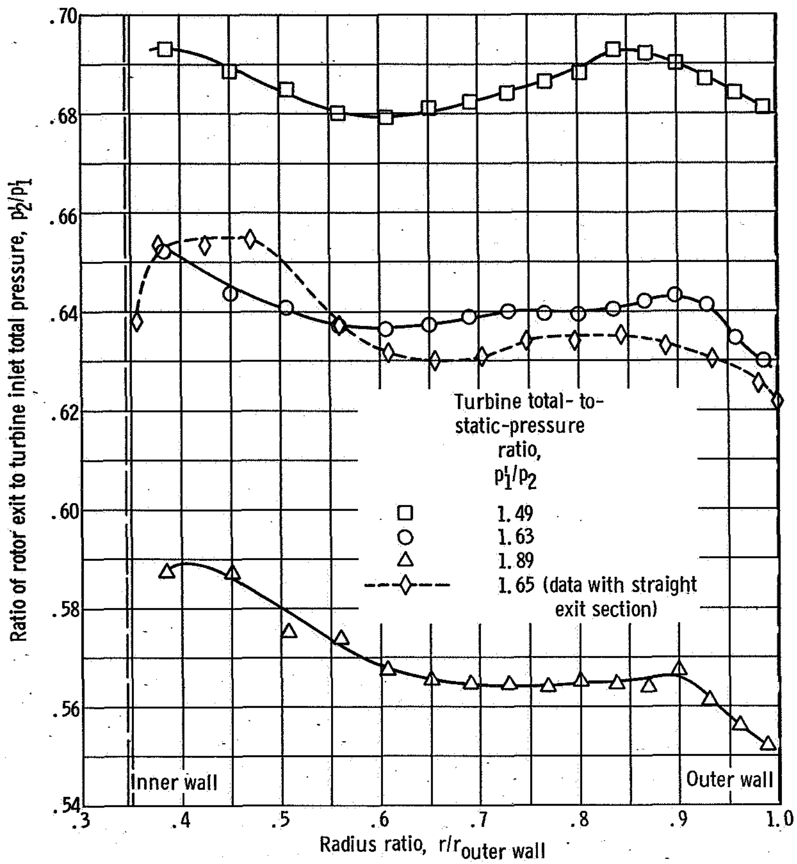

Figure 10. - Variation of turbine exit total pressure with radius ratio.

pressure were divided by the turbine inlet total pressure in order to minimize any effects of changes in turbine inlet total pressure during the tests. Also shown is a dashed line representing data taken with a straight exit section at a turbine pressure ratio of 1.65. Comparing turbine data taken with the straight exit section with data taken with the diffuser shows the curves to be similar except for minor variations near the inner wall. Figure 11 shows the radial variation of diffuser exit total pressure from the inner to outer wall to be small for all three pressure ratios investigated. Thus, the exit diffuser reduces the radial total pressure variation present at the diffuser inlet.

Diffuser Effectiveness

Performance of a diffuser can be represented in terms of pressure recovery. A parameter commonly used is the ratio of static pressure rise through the diffuser to the diffuser inlet impact pressure. This parameter may be seen plotted in figure 12 against turbine blade-jet speed ratio. The three symbols shown on this figure represent data taken at the three turbine pressure ratios at design equivalent speed where the previously

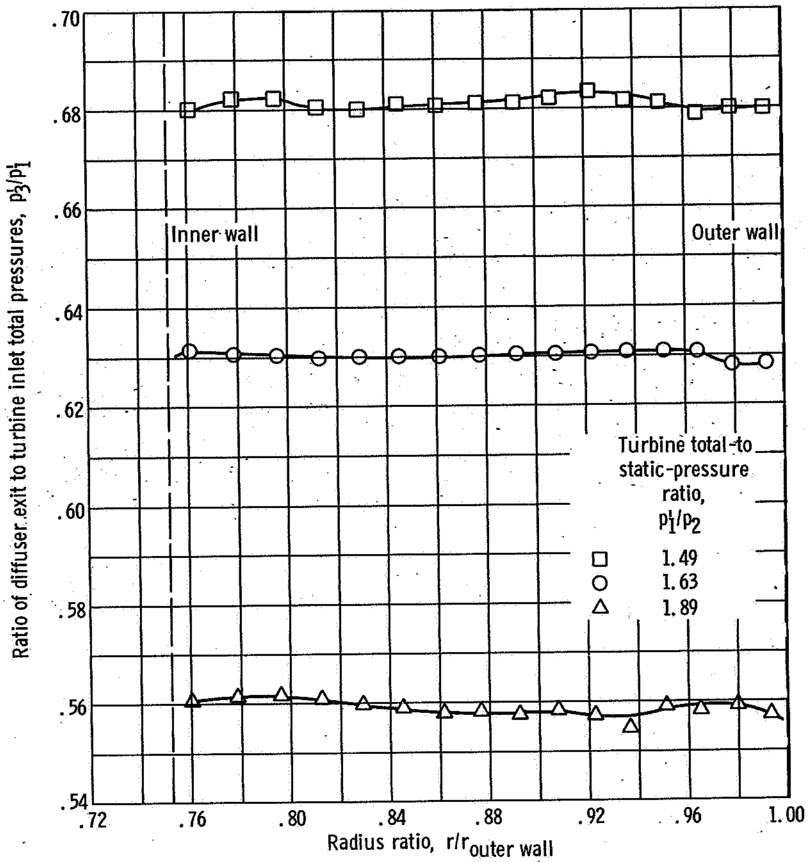

Figure 11. - Variation of diffuser exit total pressure with radius ratio.

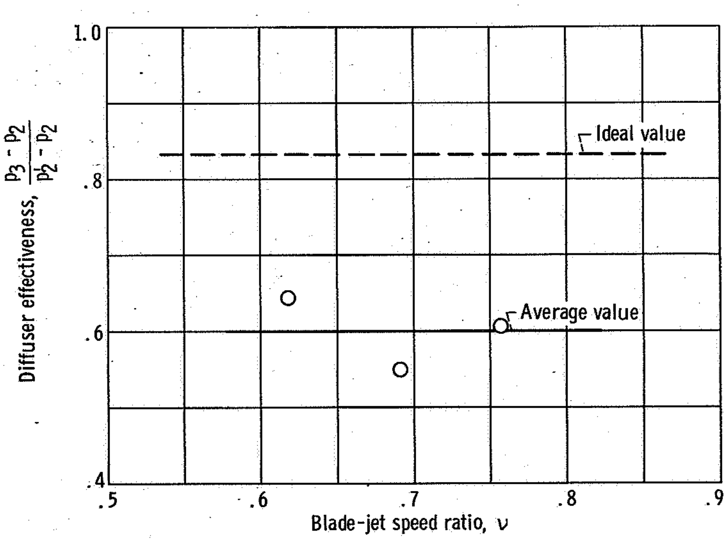

Figure 12. - Variation of diffuser performance with blade-jet speed ratio.

mentioned radial surveys were made. Figure 12 shows the average value of diffuser effectiveness to be about 0.6, over a range of blade-jet speed ratios from 0.6 to 0.8.

Also shown in the figure is the diffuser effectiveness for isentropic incompressible diffusion with the same area ratio. The value is 0.84 and is shown as a dashed line. The experimental value of 0.6 is 71 percent of this isentropic value.

SUMMARY OF RESULTS

A performance evaluation of a 6.02-inch (15.29-cm) radial-inflow turbine was made with an exit diffuser. The evaluation was made, using argon as the working fluid, over a range of speeds and pressure ratios. Turbine inlet conditions were fixed to correspond to design Reynolds number for design equivalent speed and design pressure ratio operation. The results of the investigation can be summarized as follows:

1. At design equivalent speed and pressure ratio, the turbine static efficiencies before and after diffusion were 0.825 and 0.865, respectively.

2. The turbine total efficiencies, as obtained from survey data at design equivalent speed, indicated that the total efficiency decreased approximately 2 percent across the diffuser. The leaving loss accounted for less than 1 percentage point in efficiency.

3. Radial traverse measurements behind the rotor indicated that the diffuser had a minor effect on the rotor exit conditions. Similar measurements at the diffuser exit indicated that the radial variation in total pressure had been substantially decreased by the diffuser.

4. The ratio of the diffuser static pressure recovery to the diffuser inlet impact pressure was approximately 0.6. This recovery is about 71 percent of the isentropic incompressible value for the same area ratio.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, August 22, 1967,
129-01-05-12-22.

REFERENCES

1. Bernatowicz, Daniel T.: NASA Solar Brayton Cycle Studies. Paper presented at the Symposium on Solar Dynamics Systems, Solar and Mechanical Working Groups of the Interagency Advanced Power Group (Washington, D.C.). Sept. 24-25, 1963.
2. Kofskey, Milton G.; and Holeski, Donald E.: Cold Performance Evaluation of a 6.02-Inch Radial Inflow Turbine Designed for a 10-Kilowatt Shaft Output Brayton Cycle Space Power Generation System. NASA TN D-2987, 1965.
3. Holeski, Donald E.; and Futral, Samuel M., Jr.: Experimental Performance Evaluation of a 6.02-Inch Radial-Inflow Turbine Over a Range of Reynolds Number. NASA TN D-3824, 1967.

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